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Preface

# Collisional orogenesis in the geological record and modern analogues

Plate tectonic principles have provided a unifying conceptual framework for understanding the evolution of modern and Cenozoic orogens. Over the past 30 years, application of these principles to the understanding of Mesozoic, Paleozoic and Proterozoic orogens has gained almost universal acceptance among geoscientists (e.g., Wilson, 1966; Dewey and Bird, 1970; Coward and Ries, 1986; Hoffman, 1988; Windley, 1995). To what extent plate tectonic processes operated in the Archean remains controversial (e.g., Hamilton, 1998). However, the poorer preservation of ancient orogenic belts means that some important techniques used to understand modern belts (e.g., ocean floor record, faunal and paleomagnetic data) are much less useful, and tectonic models become less actualistic with increasing age. Geoscientists studying ancient belts have developed other approaches so that data collected from modern and ancient orogens are generally different. Recent technological advances in geochronology and paleomagnetism, and conceptual advances in other fields, have vastly improved our knowledge of ancient orogenic belts such that realistic modern analogues can now be entertained. On the other hand, well-constrained ancient orogens can supply the third and fourth dimensions (depth and time) that are generally missing from modern orogens. The goal of IGCP project 453 is to bring together these two groups of geoscientists with complementary expertise in order to provide a more comprehensive understanding of orogens and their evolution through the ages.

The first annual meeting of IGCP 453 (October 2000) focused on the evolution of the modern flat-slab subduction in the Andes and was organized by Victor Ramos, University of Buenos Aires and attracted 45 participants from 10 countries. A special issue of the *Journal of South American Earth Sciences* entitled “Flat slab subduction in the Andes” with Victor Ramos and Brendan McNulty as guest editors is an outgrowth of this meeting. The papers in this volume provide the characteristics of flat-slab subduction, which may be used as a template for the recognition of flat-slab subduction in ancient orogens.

This volume is an outcome of the 2001 annual conference/field workshop, which was organized by Gerard Stampfli, University of Lausanne. The meeting focused on collisional orogens and was held in Sion, in the Swiss Alps, a classical example of a collisional orogen. The preconference field trip focused on the external nappes (classical Helvetic domain) of the Alps, including the Variscan basement. The postconference trip featured the internal nappes (classical Penninic domain) and exotic nappes in the Pre-Alps (Stampfli and Borel, 2002). We asked participants at this meeting to contribute to a special volume under the general title “Collisional orogenesis in the geological record and modern analogues.” We have 14 contributions that not only provide an overview of the geology of several important orogens. Collectively, these papers illustrate the diversity of disciplines and techniques that must be applied to tectonic studies of collisional orogens as well as some useful insights into the development of collisional orogens through time and space.

Seven papers deal with Variscan and Alpine collisional orogenesis in Europe and Asia. von Raumer et al. show that the Alpine orogenic belt contains a number of “pre-Variscan” terranes that originated along the northern Gondwanan margin in the Neoproterozoic and early Paleozoic as “peri-Gondwanan”

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terranes. They present a series of reconstructions for the Paleozoic era that show the evolution of these “peri-Gondwanan” terranes, from an archipelago-like continental ribbon, their relationship to the evolution of the Rheic and Prototethys ocean, and how they were reworked during the Variscan and Alpine orogenic cycles. This paper is an example of the application of modern geodynamic principles to the understanding of Paleozoic geology, and the additional insights provided by reconstructions that emphasize plate boundaries in addition to the positions of continents and major terranes.

There is a consensus that repeated reactivation of continental fault zones is a characteristic feature of continental deformation (e.g., Holdsworth et al., 2001). However, the degree to which the style of orogenesis is influenced by earlier tectonism is uncertain. The contribution of Khudoley and Guriev demonstrates the influence of the evolution of a passive margin on the style of orogenesis that subsequently takes place along that margin. The eastern Siberian craton is dominated by a thick Mesoproterozoic to Mesozoic passive margin succession that was deformed and thrust onto the Siberian craton during Mesozoic orogeny. The authors document several rifting events including the Neoproterozoic, early Paleozoic and Late Devonian, each event being characterized by listric normal faulting and half-graben development. The Neoproterozoic (ca. 1.0–0.95 Ga) rifting event provided weakened zones that were reactivated as thrusts during Mesozoic orogeny along the margins of the Siberian craton.

The paper by Oxman provides a detailed overview and plate tectonic model for the Mesozoic Verkhoyansk-Kolyma orogen of north-eastern Asia, which lies between the ancient Siberian platform and Mesozoic–Cenozoic Koryak–Kamchatka accretionary orogen. Oxman proposes that the Verkhoyansk–Kolyma orogen is comprised of a collage of terranes that combined into the composite Kolyma–Omolon superterrane. The orogen consists of a continental foreland and a collisional belt, known as the Chersky collisional belt, which is characterized by dismembered ophiolitic allochthons, fault slices of Paleozoic–early Mesozoic preorogenic rocks and synorogenic Mesozoic volcano-sedimentary and granitoid rocks. In the hinterland of the orogen, Paleozoic–early Mesozoic complexes are polydeformed. Three Mesozoic deformational events are recognized, the first stage in the Middle to latest Jurassic is attributed to the formation of the Kolyma–Omolon superterrane and its convergence with respect to the Siberian platform. Collision of the Kolyma–Omolon microcontinent with the Verkhoyansk continental margin in the latest Jurassic Cretaceous produced the second phase of deformation. According to Oxman, the Kolyma–Omolon microcontinent acted as indentor. The third stage of deformation in the Early Cretaceous resulted from the collision of the Alaska and Siberian continental margins.

Two papers (Reddy et al.; Abad et al.) illustrate the importance of understanding the behaviour of phyllosilicates during orogenesis. Reddy et al. provide structural and geochronological data from an extensive region of the Italian Alps where a large shear zone (ca. 50 km perpendicular to strike), previously interpreted to be related to convergence, is reinterpreted to reflect post-accretionary extension, an event which also results in exhumation of eclogites. They constrain the age of deformation and provide a complex kinematic model involving localized preservation of older fabrics, synextensional convergent fabric development and subsequent extension associated with regional folding. The authors’ approach is to combine macroscopic and microscopic analyses of fabric development with high-precision radiometric data. Detailed intra-grain Ar–Ar analyses on white micas show that the age data are complicated by excess $^{40}$Ar in eclogite facies rocks and by partial Ar loss during Alpine reheating. They interpret the range in ages yielded by Rb/Sr data from white micas in different kinematic domains to reflect variable timing of syn-kinematic mica recrystallization. They also show how this approach can record the exhumation of eclogites.

Abad et al. illustrate that structural field studies combined with the analytical investigation of phyllosilicates provide constraints on the tectono-thermal evolution of the Tien Shan belt in the Kyrgyz Republic. The authors use several techniques to analyze white mica including high-resolution TEM and correlate atomic structure of the mica with different deformational processes and cleavage development in orogens. For example, they show that there is a clear difference in structure and composition between micas found in axial planar cleavages and those related to thrusting.

According to Dickerson, the Tien Shan belt provides a modern analogue for intra-plate mountain building as a far-field response to continent–continent collision between India and Asia. The Ancestral Rocky Mountains of North America may be a Paleozoic example of this process. Dickerson maintains that the array of uplifts and basins and the overall structural style of the Tien Shan may assist in recognizing intra-plate mountain belts in the geologic record. On the other hand, exhumed deep crustal shear zones in the Ancestral Rockies provide insights into the strain partitioning responsible for uplifts and basin formation in the shallow crust.

Low-pressure metamorphism in collisional orogenies is commonly interpreted to be a late-stage feature, associated with extension and orogenic collapse. Arenas and Martinez Catalan, however, show that units in adjacent to the Mondonedo thrust sheet in the NW Iberian Massif underwent a complex tectonic evolution that began with a medium-pressure metamorphic and crustal thickening event during late Paleozoic (Variscan) convergence but evolved into low-pressure metamorphism associated with thinning and exhumation during convergence. More generally, Arenas and Martinez Catalan propose that low-pressure metamorphism can develop by tectonic denudation of allochthons during emplacement or by thinning and extension of the footwall during thrusting.

Five papers deal with a variety of complex processes associated with the collision of terranes in accretionary orogens. Models for the formation of oroclinal bends in accretionary orogens are controversial. Johnston and Acton interpret a 20° counterclockwise deflection in the fault-controlled southwestern coastline of southern Vancouver Island to reflect the development of an orocline as a response to seamount accretion in the Eocene. They consider that these events resulted in a fold-and-thrust belt and in local extension resulting in basin formation. Timing constraints indicate that oroclinal development resulted from the Eocene accretion of seamounts of the Crescent terrane of the Coast Ranges. More generally, the authors propose that oroclinal orogeny that involves the buckling and rotation of a linear crustal beam about a vertical axis can significantly affect the geometry, structure and character of an orogenic belt even if, as is the case in southern Vancouver Island, the amount of rotation is relatively minor.

There are more than 40 hotspots beneath the modern oceanic crust (Crough and Jurdy, 1980), and no modern ocean could be consumed without interaction between the underlying plume and a continental margin. This observation implies that interactions between plumes and subduction zones should be common in the geologic record (Murphy et al., 1998). Murphy et al. interpret the Crescent terrane as a reflection of a the ancestral Yellowstone plume, at a time when that plume resided beneath oceanic crust. According to these authors, the 60–50-Ma Crescent terrane formed in a shallowing-upward Loihi-type oceanic setting and was emplaced into ca. 20-Ma crust. The presence of subaerial lavas is used to calculate a minimum uplift due to the plume and a minimum buoyancy flux that is comparable with modern Yellowstone. Using plate reconstructions, and the time interval between formation and accretion of the terrane, the authors calculate a paleolongitude that is similar to that of modern Yellowstone. As published paleomagnetic data indicate that the terrane was formed at a paleolatitude similar to that of the Yellowstone plume, this would imply that the plume responsible for the Crescent terrane was in a similar location to that of modern Yellowstone. More generally, this paper shows that stratigraphy of plume-generated seamounts can be used to geodynamically constrain the flux of the plume responsible for them, and that the inevitable interaction between a plume and a subduction zone profoundly affects the style of orogenesis.

The Neoproterozoic and early Paleozoic is a pivotal time interval in Earth history because a succession of events, including worldwide orogeny, rapid continental growth, profound changes in ocean geochemistry and an explosion in biological activity, led to irreversible global change (e.g., Knoll and Walter, 1992, Knoll, 1994; Hoffman, 1999). Paleocontinental reconstructions for this time interval, however, are poorly constrained. Along the northern Gondwanan margin, a number of terranes, (collectively termed "peri-Gondwanan") are believed to have faced an open ocean such that their evolution provides important constraints on continental reconstructions. The papers by Keppie et al., Gutierrez-Alonso et al. and Sanchez-Garcia et al. document various aspects of the evolution of these terranes and provide an example of the use of modern analogues to understand ancient orogens. Their common theme is that the Mesozoic–Cenozoic evolution of western North America provides a modern analogue for the evolution of these peri-Gondwanan terranes. Keppie et al. show that the evolution of these terranes involve a protracted (ca. 750–600 Ma) history of subduction and arc magmatism that diachronously switched to rift magmatism between 590 and 540 Ma, an event attributed to ridge–trench collision and the generation of a San Andreas-style transform margin. Some of these terranes (e.g., Avalonia, Carolina) rifted from Gondwana in the Early Ordovician and had collided with Laurentia by the Late Ordovician. Other terranes (e.g., Oaxaquia, Cadomia, Iberia, Bohemia) remained along the Gondwanan margin until their collision and transfer to Laurentia–Baltica during late Paleozoic orogenic events. It is apparent that the terranes were transferred in a variety of ways. Drawing on recent tectonic analogues, Keppie et al. evaluate three models of terrane transfer: accordion, bulldozer and Baja models and apply them to the transfer of peri-Gondwanan terranes to Laurentia and Laurussia.

Gutierrez-Alonso et al. present new U–Pb detrital zircon data from obtained by laser ablation ICP-MS from Neoproterozoic and early Paleozoic sedimentary rocks in Iberia and Brittany. The data show a wide range of age populations, which taken together can constrain the source region. The absence of Mesoproterozoic (1600–900 Ma) zircons in SW Iberia, Brittany and in most of Bohemia suggests derivation from West African basement, a region where orogenic events of this age are unknown. In contrast, NW Iberia, NE Bohemia and Moravo-Silesia contain abundant Mesoproterozoic zircons, suggesting derivation from the South American craton, where orogenic events of this age are widespread. The data further suggest that terranes with differing basement signatures (e.g., NW Iberia, SW Iberia) were juxtaposed prior to the Ordovician (ca. 465 Ma) deposition of the Armorican quartzite. To achieve this juxtaposition, the authors propose that NW Iberia was translated relative to SW Iberia along a continental transform fault in a manner analogous to the dextral translation of terranes along the San Andreas transform.

According to Sanchez-Garcia et al., ridge–trench collision followed by overriding of the ridge not only terminated subduction, but, in the Ossa Morena Zone of Iberia, produced voluminous bimodal rift-related igneous rocks that culminated in the formation of a new oceanic basin, possibly the Rheic Ocean. An Early Ordovician breakup unconformity provides evidence of a significant tract of new ocean by this time. These authors interpret new and previously published geochemical data on the igneous rocks and show that early magmatism produced crustally derived felsic magmatism and core-complex formation. This was followed by a more voluminous phase of mafic magmatism with geochemical traits similar to modern OIB, attributed by the authors to derivation from a variably enriched asthenospheric source. One of the important features of this paper is that the model presented implies a transition from subduction-related orogenic activity along a continental margin to ridge collision, rift-related magmatism and ocean generation.

Two contributions (Solari et al., Roberts) give detailed analyses of the complex tectonothermal evolution in two classical collisional orogens, the Grenville orogen as preserved in Mexico, and the Caledonides in Scandinavia. The paper by Solari et al. provides and example of ca. 1.1–0.9 Ga orogenesis recorded in the basement rocks of the Oaxaquia microcontinent in Mexico. Broadly contemporaneous tectonothermal events took place in various parts of the Grenvillian orogen in Laurentia and Amazonia, and these events are collectively thought to represent the amalgamation of the supercontinent, Rodinia. Solari et al. focus on the northern part of the largest inlier of Grenville-aged rocks in Mexico. This inlier contains a ca. 1.0-Ga anorthosite–mangerite–charnockite–granite (AMCG) suite, and para- and orthogneisses that record two major tectonothermal events: a ca. 1.1-Ga event that produced migmatites, metamorphic differentiation and isoclinal folds followed by ca. 1.0-Ga event characterized by granulite facies to upper amphibolite facies metamorphism and polyphase deformation. The second event is defined as the Zapotecan orgeny and is related to crustal thickening in either a subduction-related or collisional orogenic environment.

The contribution of Roberts shows how the subdivision of the Caledonian orogen in Scandinavia into a series of major allochthons, with parautochthonous and autochthonous units in the foreland, provides a tectonostratigraphic and palaeogeographical framework for understanding four major orogenic events that affected the region in the Paleozoic. Taken together, these units record an example of the destruction and telescoping of a passive margin, with thrusting, accretion of outboard terranes followed by continent–continent collision. The Finnmarkian (Late Cambrian) and Trondheim (Early Arenig) orogenic events involved subduction, contraction and accretion between Baltica and/or an adjacent microcontinent and arcs within the early Paleozoic Iapetus Ocean. The Middle–Late Ordovician Taconian event is interpreted as arc-accretion event that occurred along the Laurentian margin that was subsequently transferred to Baltica. The middle Silurian–Early Devonian Scandian event involved continental collision between Baltica and Laurentia in which the Baltican margin was subducted beneath Laurentia to depths greater than 120 km. Collisional orogenesis was followed by rapid exhumation, orogenic collapse, widespread extension and basinal formation.

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